Antiproton Stacking and Cooling

Paul Derwent

July 21, 2003

Parameter Goals

- Goals
  - Average Stacking Rate 40×10^{10} pbars/hour
  - Stack at this rate for at least 15 hours
  - Final Stack Parameters
    - Size = 625×10^{10} pbars
    - Transverse emittance < 15π-mm-mrad (95% normalized)
    - Longitudinal emittance < 50 eV-Sec
- Inputs
  - Collect 280×10^{6} antiprotons from the target every 2 seconds
    - Transverse emittance = 335π-mm-mrad (95% normalized)
    - Momentum Spread = 4%
    - Bunch lengths < 1.5 nS

Strategy

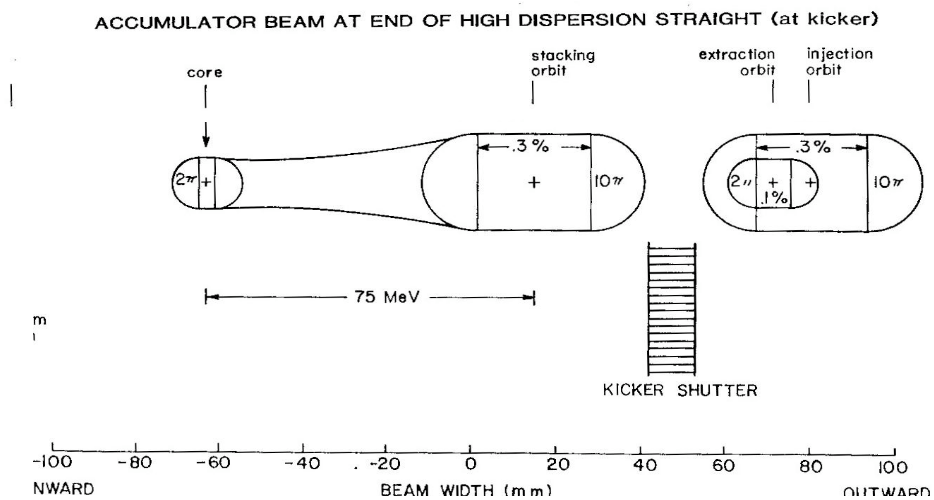
- Present Run II Operations
  - Accumulator Core is the final repository for antiprotons
    - Bandwidth
    - Momentum aperture
    - Stacktail gain slope
  - 1/N effect in stochastic cooling limits stack size to ~300×10^{10} pbars
- Run II Upgrades
  - The Recycler is the final repository for antiprotons
  - Electron cooling in the Recycler greatly reduces the 1/N effect
    - Larger average/peak stacking rate ratio
    - Larger stacks ~600×10^{10}
  - Accumulator Stacktail is optimized to handle larger flux by larger bandwidth and smaller gain slope
  - Greatly reduced Accumulator core size is also a result of larger bandwidth and smaller gain slope
  - Reduced Accumulator core size and high stacking rates require frequent and rapid transfers between the Accumulator and the Recycler

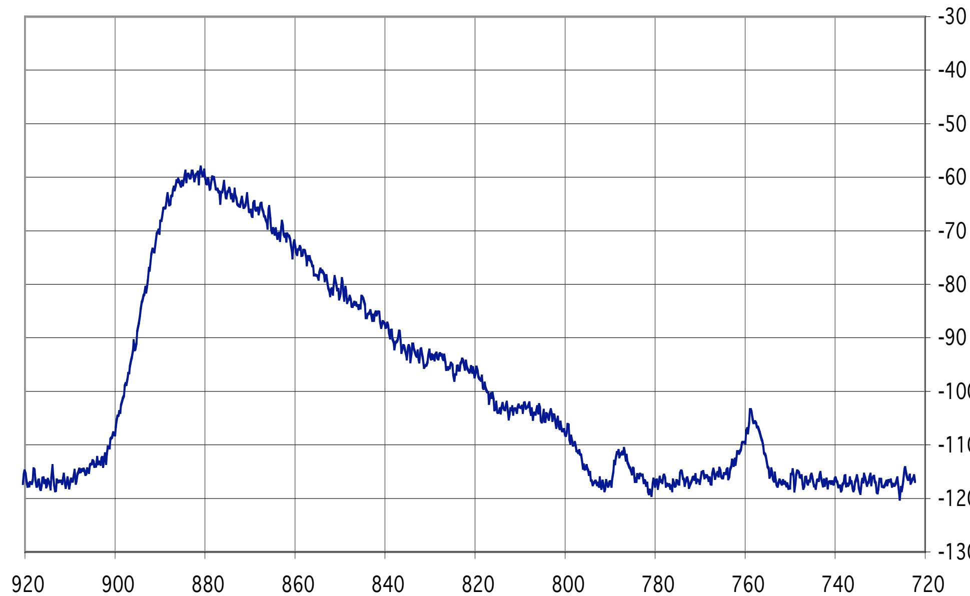
Antiproton Stacking Process

- Debuncher Bunch Rotation
  - Exchange
    - Large Momentum spread of 4% (360 MeV)
    - Short bunches < 1.5 nS (95%)
  - For
    - Small momentum spread of 0.4% (36 MeV)
    - Coasting beam
- Debuncher Cooling
  - System Configuration
    - Liquid Helium front end (T_{eff}=30K)
    - Bandwidth = 4-8 GHz Subdivided into 4 bands
    - Available kicker power
      - 2400 Watts/ plane (transverse)
      - 4800 Watts (momentum)
  - Cooling Rate Specs.
    - Momentum: 36 MeV to 6 MeV in 1.9 Seconds
    - Transverse: 335π-mm-mrad to 45 π-mm-mrad (95% normalized) in 1.9 seconds

Antiproton Stacking Process

- Accumulator Stacktail Cooling
  - ➢ Process
    - Beam is injected onto the Injection Orbit
    - Beam is
      - Bunched with RF
      - Moved with RF to the Stacking Orbit
      - Debunched on Stacking orbit
    - Stacktail pushes and compresses beam to the Core orbit
    - Core Momentum system gathers beam from the Stacktail
    - Accumulator Transverse Core Cooling system cools the beam transversely in the Stacktail and Core





Antiproton Stacking Process

- Accumulator Stacktail Cooling
  - Specifications
    - Injection pulse width: 6 MeV
    - Stacktail:
      - Bandwidth = 2-6 GHz
      - Width = 42 MeV
      - Gain slope = 8 MeV (can handle 90×10^{10}pbars/hr)
      - Power = 550W into 6400Ω
    - Core momentum
      - Bandwidth = 4-8 GHz
      - Aperture = 9.6 MeV
      - Gain slope = 5 MeV (can handle 90×10^{10}pbars/hr)
      - Stacksize = 34×10^{10}pbars
    - Extraction
      - Longitudinal emittance: 10eV-sec
      - Transverse emittance: 10π-mm-mrad (95% normalized)
      - Stacking interval: 30 minutes
      - Transfer size: 22.5×10^{10}pbars

Antiproton Stacking Process

- Recycler Electron Cooling
  - Every $^{1}/_{2}$ hour an injected batch of 22×10^{10}pbars in 10 eV-Sec and 10 π-mm-mrad phase space is injected into the Recycler
    - Transfers between the Accumulator and the Recycler
      - Are done on "clock event"
        - ~instantaneously
        - No more mini-shot setup
      - A 50% dilution is assumed to occur on each transfer
        - 15 eV-Sec and 15 π-mm-mrad phase space
    - Transverse stochastic pre-cooling of the injected batch
      - To bring the transverse emittance of the injected batch within the reach of the electron cooling
      - The injected batch is kept separate from the main "core" by barrier buckets
      - Transverse stochastic cooling systems are "gain gated"
        - Low density injected batch – fast stochastic cooling
        - High density core – slow stochastic cooling

Antiproton Stacking Process

- Recycler Electron Cooling
  - Every $^1/_2$ hour, the previous injected batch is merged into the core with barrier bucket manipulations to make room for the new injected batch
  - The Recycler Core
    - Is cooled mainly with electron cooling in all 3 planes
    - Weak transverse stochastic cooling for high amplitude particles
    - Intra-beam scattering (IBS) is "shut-off"
      - Recycler
        - operates below transition
        - has low dispersion
        - has smooth lattice functions
      - The Core is squeezed with barrier buckets so that it occupies only 20% of the machine circumference
      - The transverse emittance is cooled to less than 3π-mm-mrad (95% normalized) so that the beam temperature in all 3 planes is equal

Antiproton Stacking and Cooling Projects

- Accumulator Stacktail Upgrade
  - Project Leader: Paul Derwent
  - Major Objectives: Upgrade the Stacktail system to handle 90×10^{10} pbars/hour
    - Increase bandwidth of the system to 2-6 GHz
    - Reduce gain slope ~10 MeV
- Rapid Antiproton transfers from the Accumulator to the Recycler
  - Project Leader: Elvin Harms
  - Major Objectives:Transfer Accumulator core to the Recycler
    - in less than 1 minute every 30 minutes
    - <50% emittance dilution
    - 95% transfer efficiency
- Electron Cooling in the Recycler
  - Project Leader: Sergei Nagaitsev
  - Major Objectives: Install a 4.3 MV Pelletron in the Recycler
    - 500 mA of electron current
    - 20 meters of cooling section

Antiproton Stacking and Cooling Projects

WBS	Task	In Charge	Labor Est ($K)	Labor Cont	M&S Est ($K)	M&S Cont	Start
1.3.3	**Pbar Stacking and Cooling**	**Paul Derwent**	**3,856**	**55%**	**2,256**	**46%**	**1/1/03**
1.3.3.1	Stacking and Cooling Integration	Sergei Nagaitsev	447	20%	0	0%	3/3/03
1.3.3.2	Debuncher Cooling	Paul Derwent	22	60%	0	0%	3/1/03
1.3.3.3	Stacktail Cooling	Paul Derwent	746	40%	1,171	40%	3/1/03
1.3.3.3.1	Momentum	Paul Derwent	371	41%	1,004	40%	3/1/03
1.3.3.3.2	Betatron	Paul Derwent	375	40%	167	40%	3/3/03
1.3.3.4	Recycler Stacking and Cooling	S Nagaitsev	786	59%	0	0%	5/1/03
1.3.3.4.3	Measure Parameters and Develop Commissioning Plan	S Nagaitsev	0	0%	0	0%	10/2/03
1.3.3.4.7	RR Beam Studies and Commissioning	S Nagaitsev	385	60%	0	0%	10/1/03
1.3.3.4.8	RR Vacuum Upgrade	S Nagaitsev	0	0%	0	0%	10/1/03
1.3.3.5	Electron Cooling	Sergei Nagaitsev	1,063	70%	568	48%	3/3/03
1.3.3.5.1	Commission Full Beamline	Sergei Nagaitsev	539	86%	55	77%	3/3/03
1.3.3.5.2	Design and procure components	Jerry Leibfritz/Sergei Nagaitsev	196	42%	375	42%	9/1/03
1.3.3.5.3	Disassemble Wideband Facility	Jerry Leibfritz/Sergei Nagaitsev	32	57%	22	58%	2/2/04
1.3.3.5.4	Transport Components to MI-31	Jerry Leibfritz	17	60%	24	60%	3/1/04
1.3.3.5.5	Install Pelletron at MI-31	Jerry Leibfritz/Sergei Nagaitsev	57	60%	37	60%	2/2/04
1.3.3.5.6	Commission Pelletron	Sergei Nagaitsev	38	60%	0	0%	8/11/04
1.3.3.5.7	Install E-Cool Transferline	Jerry Leibfritz	14	40%	23	40%	5/3/04
1.3.3.5.8	Modifications to MI/RR	Jerry Leibfritz	9	45%	15	52%	5/1/03
1.3.3.5.9	Install Cooling Section in RR	Jerry Leibfritz/Sergei Nagaitsev	30	48%	17	40%	6/28/04
1.3.3.5.10	Commission Cooling Section	Sergei Nagaitsev	30	86%	0	0%	8/23/04
1.3.3.5.11	Commission Electron Cooling	Sergei Nagaitsev	101	60%	0	0%	9/24/04
1.3.3.6	Rapid Transfers	E Harms	792	64%	517	60%	1/1/03
1.3.3.6.1	Document Fast Transfer scheme	E Harms	1	40%	0	0%	4/1/03
1.3.3.6.2	Beam Line Regulation	E Harms	25	53%	12	40%	11/17/03
1.3.3.6.3	RT Software	E Harms	249	75%	0	0%	11/17/03
1.3.3.6.4	Oscillation Feedback and Control	E Harms	108	59%	0	0%	1/1/03
1.3.3.6.5	Diagnostics	E Harms	393	60%	505	60%	1/16/04
1.3.3.6.6	Commission Fast Transfers	E Harms	16	60%	0	0%	3/4/05

Accumulator Stacktail Upgrade Project Strategy

- Design margin for flux = 90x10^{10}pbars/hour

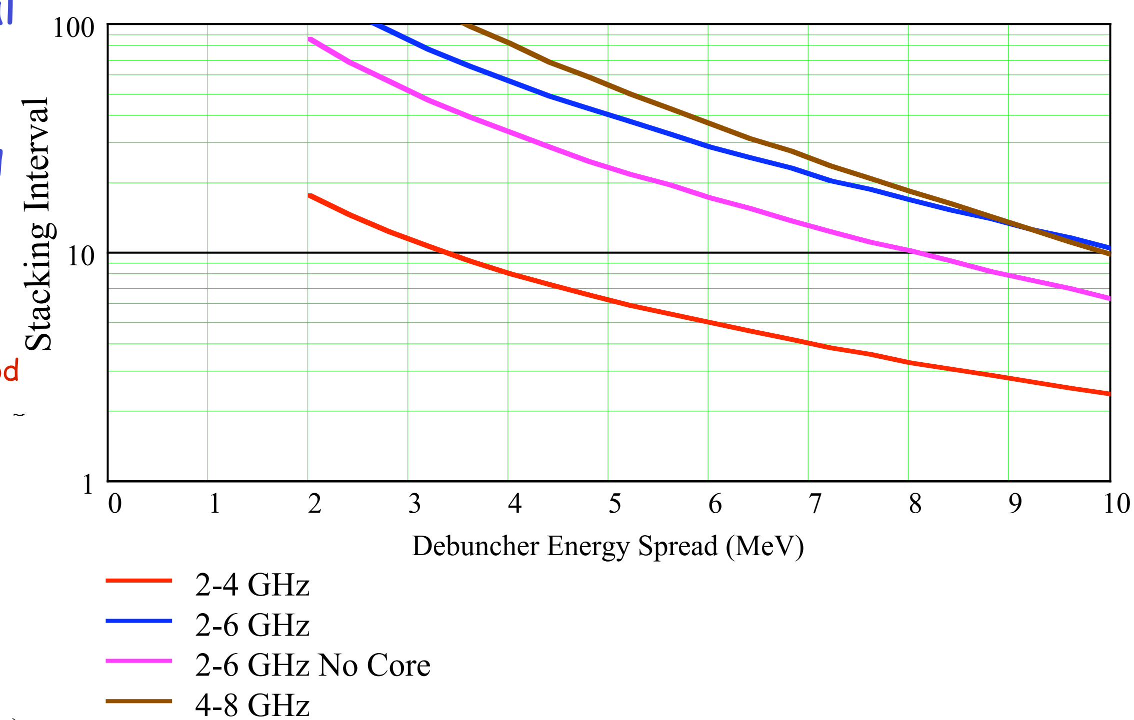
$$\Phi_o = \frac{|\eta| W^2 E_d}{f_o \beta p c \ln\left(\frac{f_{max}}{f_{min}} \right)}$$

- The best way to increase flux is to increase the bandwidth
- Large E_d needs a large momentum aperture or results in a low final core density
- Energy Aperture and Stability
  - Would like energy aperture as big as possible to get a large core density
  - For system stability, operate at frequencies where Schottky bands do not overlap
  - Strategies
    - Reduce η
      - Increases β functions – decreases aperture
      - Increases intra-beam scattering heating
    - Reduce momentum aperture of cooling system
    - Core Momentum system with higher bandwidth
      - Energy aperture of core is limited by "bad" mixing between pickup and kicker at high frequencies

Accumulator Stacktail Upgrade Project Strategy

- Core Density and Stacking Interval
  - Particles to be transferred must be inside desired Recycler longitudinal emittance
  - Desire long stacking interval
    - Small Debuncher energy spread ΔE_{bd}
    - Large energy aperture $\Delta E_s+\Delta E_c$
    - Small characteristic energy slope (E_d)

Stacktail Bandwidth (GHz)	Core Bandwidth (GHz)	E_{ds} (MeV)	E_{dc} (MeV)	$\Delta E_s+\Delta E_{bd}$ (MeV)	ΔE_c (MeV)	Fraction Unstacked (%)
2-4	4-8	20	5	77.4	9.6	50
2-6	4-8	8	5	48.4	9.6	66
2-6	2-6	8	8	45.2	12.8	55
4-8	4-8	5	5	33.9	9.6	72

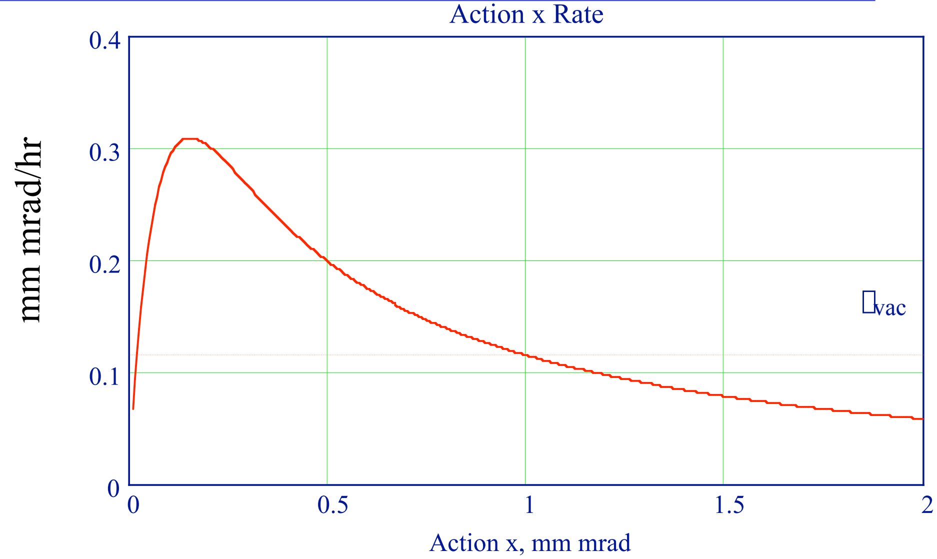


Rapid Transfers Project Strategy

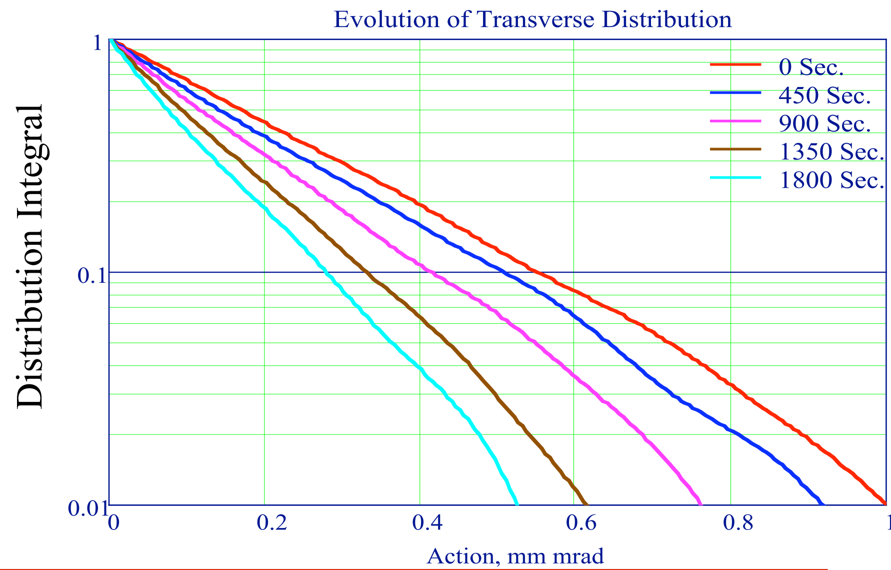
- Transfers are done on clock event
  - Halt to stacking
  - Accumulator RF Extraction
  - Transfer to the Recycler
  - Recycler Barrier Bucket manipulation
  - Return to stacking
- P1, P2, and AP1 power supplies ramp on every clock event
  - No more bi-modal operation of AP1
- Fast Feedback
  - Random oscillations are corrected by injection dampers in the Main Injector and Recycler
    - 1 kV in ~80 turns will damp 2π-mm-mrad (95% normalized) oscillation
  - 8 GeV transfer line magnet power supplies regulation specification to 2π-mm-mrad
- Slow Feed-Forward
  - Transfer line reference orbit
    - Transfer line BPM system
  - Injection oscillations
    - Turn-by-turn info provided by damper systems.

Recycler Stochastic Pre-cooling and Vacuum

- Needed to transversely pre-cool 22×10^{10}pbars injected from the Accumulator for $^1/_2$ hour to bring the transverse emittance within the electron beam



- Evolution of the injected batch with 22×10^{10} pbars using a Q=1 2-4 GHz Transverse Stochastic Cooling system, 7π-mm-mrad/hr vacuum growth rate



Recycler Electron Cooling Project Strategy

- Decide on whether to do longitudinal cooling and/or betatron cooling
  - Longitudinal cooling rate independent of β function
    - Important for the Recycler
  - Transverse cooling rate proportional to $\beta^{1/2}$
    - Not as important for the Recycler
- Design for minimum angular spread in electron beam
  - Cooling section solenoid field quality
  - Aberrations in the beamline
  - Stability of the antiproton orbit
  - Stability of the electron optics
  - Emittance and space charge
  - Stray magnetic fields
- Decide on reasonable emittance range for optimum cooling

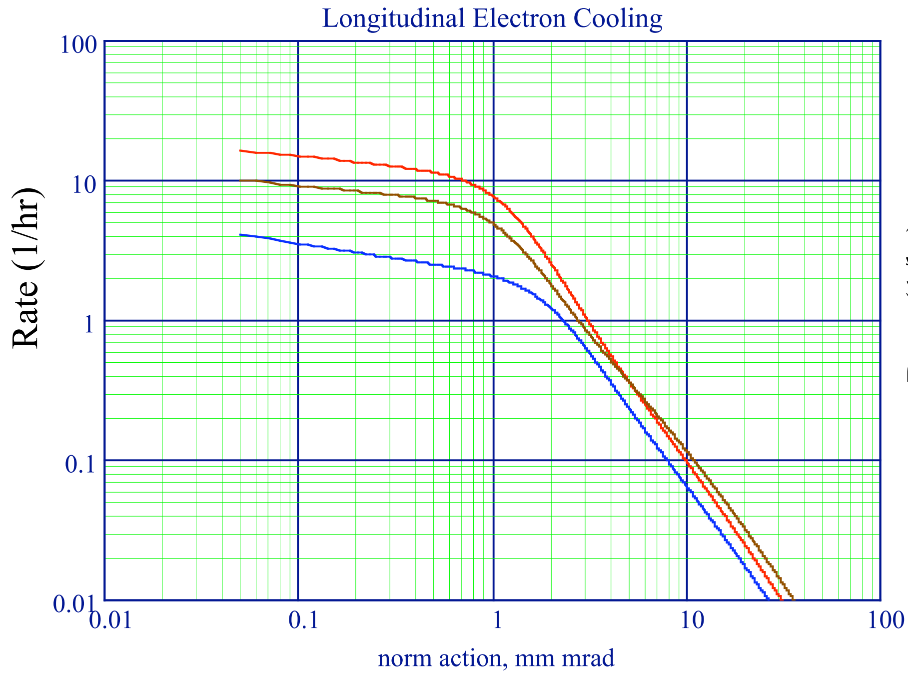
$$\sqrt{\frac{\epsilon_{95\%}}{6\beta}} \approx \Delta\theta_{electron_{spread}}$$

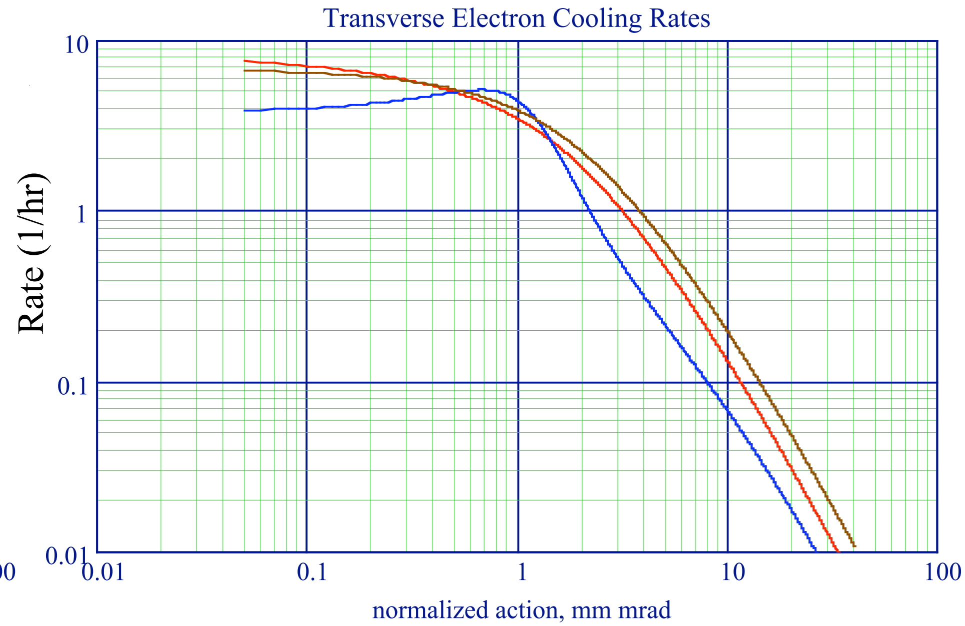
$$r^2 = \epsilon_{95\%}\beta$$

- Design electron beam size

Recycler Electron Cooling Project Strategy

- Emphasis on longitudinal cooling
- Electron Beam Current = 500 mA
- Angular spread of electron beam = 0.22 mrad
- Design cooling for transverse emittance of 3-mm-mrad (normalized) with Electron beam size = 3 mm with =22m
- Longitudinal Cooling time needed = 25 minutes





Key Parameters

Parameter	Value	Unit
Average Stacking rate	40	$\times 10^{10}$ per hour
Peak Stacking rate	45	$\times 10^{10}$ per hour
Number of particles injected into the Debuncher	280	$\times 10^{6}$
Debuncher transverse aperture	335	π-mm-mrad
Antiproton production cycle time	2	Secs
Maximum bunch length on target	1.5	nSecs.
Debuncher momentum aperture	4	%
Debuncher momentum cooling aperture	0.4	%
Debuncher final transverse emittance	45	π-mm-mrad
Debuncher final momentum spread	6	MeV
Debuncher transverse cooling common mode rejection	1.5	mm
Debuncher transverse cooling phase imbalance	3	degrees
Debuncher transverse cooling delay imbalance	1.4	pS
Debuncher momentum notch filter delay tolerance	1	pS
Debuncher momentum cooling notch filter dispersion	2.5	degrees
Debuncher to Accumulator transfer efficiency	95	%
Accumulator Stacktail Momentum bandwidth	2-6	GHz
Accumulator Core Momentum bandwidth	4-8	GHz
Accumulator Stacktail Momentum energy slope	8	MeV
Accumulator Stacktail Power	625	Watts
Accumulator Stacktail 2-6 GHz kicker impedance	6400	Ω
Accumulator Core Momentum energy slope	5	Mev
Accumulator Core Momentum cooling aperture	9.6	MeV
Accumulator Momentum cooling aperture	58	MeV

Key Parameters

Parameter	Value	Unit
Accumulator Momentum cooling aperture	58	MeV
Accumulator to Recycler transfer longitudinal emittance	10	eV-Sec
Accumulator to Recycler transfer interval	30	minutes
Number of particles extracted from the Accumulator per transfer	24	x10^{10}
Accumulator to Recycler transfer time	1	minutes
Accumulator to Recycler transfer efficiency	95	%
Accumulator core transverse emittance	10	□-mm-mrad
Recycler transverse emittance injection dilution	50	%
Recycler longitudinal emittance injection dilution	50	%
Recycler transverse Stochastic Cooling Bandwidth	>1	GHz
Recycler Transverse Stochastic cooling Center Frequency	3	GHz
Maximum Recycler Transverse emittance Growth Rate	7	□-mm-mrad/hr
Peak Stack in Recycler	620	x10^{10}
Transverse emittance of antiprotons extracted from Recycler	10	□-mm-mrad
Total Longitudinal emittance of antiprotons extracted from Recycler	50	eV-Sec
Number of bunches extracted from the Recycler	36	
Minimum longitudinal cooling rate of Electron Cooling	55	eV-Sec/hour
Minimum Electron Cooling Current	250	mA
Electron Beam alignment tolerance	0.1	mrad

Key Parameter Comparison

Parameter	Value FY06	Value FY04	Value Now	Unit
Average Stacking rate	40	12	8.5	x10^{10} per hour
Peak Stacking rate	45	18	13	x10^{10} per hour
Beam on Target	8	5	4.7	x10^{12}
Number of particles injected into the Debuncher	280	100	90	x10^{6}
Debuncher transverse aperture	335	145	145	π-mm-mrad
Antiproton production cycle time	2	1.7	2.2	Secs
Maximum bunch length on target	1.5	1.3	1.3	nSecs.
Debuncher momentum aperture	4	3.7	3.7	%
Debuncher momentum cooling aperture	0.4	0.4	0.4	%
Debuncher final transverse emittance	45	45	45	π-mm-mrad
Debuncher final momentum spread	6	5	9	MeV
Debuncher transverse cooling common mode rejection	1.5	1	<1	mm
Debuncher transverse cooling phase imbalance	3	20	30	degrees
Debuncher transverse cooling delay imbalance	1.4	10	14	pS
Debuncher momentum notch filter delay tolerance	1	1	2-3	pS
Debuncher momentum cooling notch filter dispersion	8	10	20	degrees
Debuncher to Accumulator transfer efficiency	95	95	95	%
Accumulator Stacktail Momentum bandwidth	2-6	1.7-3.7	1.7-3.7	GHz

Key Parameter Comparison

Parameter	Value FY06	Value FY04	Value Now	Unit
Accumulator Core Momentum bandwidth	4-8	4-7	2-4	GHz
Accumulator Stacktail Momentum energy slope	8	11	11	MeV
Accumulator Stacktail Power	625	280	250	Watts
Accumulator Stacktail 2-6 GHz kicker impedance	6400	6400	6400	□
Accumulator Core Momentum energy slope	5	6	11	Mev
Accumulator Core Momentum cooling aperture	9.6	12	20	MeV
Accumulator Momentum cooling aperture	58	72	80	MeV
Accumulator to Recycler transfer longitudinal emittance	10	15	15	eV-Sec
Accumulator to Recycler transfer interval	30	180	180	minutes
Number of particles extracted from the Accumulator per transfer	24	24	25	$x10^{10}$
Accumulator to Recycler transfer time	1	15	60	minutes
Accumulator to Recycler transfer efficiency	95	90	70	%
Accumulator core transverse emittance	10	10	10	□-mm-mrad
Recycler transverse emittance injection dilution	50	50	>100	%
Recyler longitudinal emittance injection dilution	50	50	>100	%
Peak Stack in Recycler	620	200	80	$x10^{10}$
Transverse emittance of antiprotons	10	10	-	□-mm-mrad
Total Longitudinal emittance of antiprotons	50	50	100	eV-Sec
Transverse stochastic cooling time @ 100e10	0.7	0.7	-	hours

Antiproton Stacking and Cooling Tasks

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1.3.3.6.3	RT Software	E. Harms	249	75%	0	0%	11/17/03
1.3.3.6.4	Oscillation Feedback and Control	E. Harms	108	59%	0	0%	1/1/03
1.3.3.6.5	Diagnostics	E. Harms	393	60%	505	60%	1/16/04
1.3.3.6.6	Commission Fast Transfers	E. Harms	16	60%	0	0%	3/4/05

Antiproton Stacking and Cooling Milestones

1.3.3	Pbar Stacking and Cooling	P. Derwent	Date	
1.3.3.3.1.1.5	Review System Design: stacktail momentum (Milestone)	P. Derwent	1/5/04	C
1.3.3.3.1.2.4	Stacktail Reconfigured (option) (Milestone)	P. Derwent	8/10/04	C
1.3.3.3.1.9	**Stacktail Momentum Operational (Milestone)**	**J. Spalding**	**11/17/05**	**A**
1.3.3.3.2.1.2	Review System Design: stacktail betatron (Milestone)	P. Derwent	11/28/03	B
1.3.3.3.2.8	**Stacktail Betatron Operational (Milestone)**	**J. Spalding**	**11/17/05**	**A**
1.3.3.4.2	Commissioning Parameters Defined (Milestone)	S. Nagaitsev	10/1/03	C
1.3.3.4.4	Commissioning Plan Evaluation (Milestone)	S. Nagaitsev	11/14/03	B
1.3.6.2.2	Review: RR and Electron Cooling Commissioning Plan (Milestone)	J. Spalding	12/16/03	A
1.3.6.2.3	Review: Phase 2-4 Transition Plan (Milestone)	J. Spalding	4/16/04	A
1.3.3.4.5	**RR Commissioned for Electron Cooling (Milestone)**	**J. Spalding**	**7/2/04**	**A**
1.3.3.5.1.11	Demonstrate beam properties at Wide Band Lab (Milestone)	S. Nagaitsev	3/19/04	B
1.3.3.5.2.1	Pelletron extension parts received (Milestone)	J. Leibfritz/S. Nagaitsev	1/1/04	C
1.3.3.5.6.1	Pelletron Installed at MI-31 (Milestone)	S. Nagaitsev	8/11/04	C
1.3.3.5.12	**Electron Cooling Operational (Milestone)**	**J. Spalding**	**1/25/05**	**A**
1.3.3.6.7	**Rapid Transfers Operational (Milestone)**	**J. Spalding**	**5/5/05**	**A**

Drivers

- Cost
  - Accumulator Stacktail Upgrade
    - Travelling Wave Tubes
  - Electron Cooling
    - Pelletron (already purchased)
    - MI31 Civil construction (already underway)
    - Transfer line components
  - Rapid Transfers
    - Transfer lines 53 MHz BPM Upgrade
- Schedule
  - Accumulator Stacktail Upgrade
    - Procurement of the Traveling Wave Tubes
  - Electron cooling
    - Recycler commissioned for Electron Cooling
    - Electron beam properties measured at Wideband
    - Electron cooling installed at MI31

Antiproton stacking Goals

- Use of Debuncher, Accumulator, and Recycler
    - Average Stacking Rate 40×10^{10} pbars/hour
    - Stack at this rate for at least 15 hours
    - Final Stack Parameters
        - Size = 625×10^{10} pbars
        - Transverse emittance < 15π-mm-mrad (95% normalized)
        - Longitudinal emittance < 50 eV-Sec